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Circuit Details and Application Note for a Versatile Plasma Probe

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A plasma-probe circuit has been developed which couples standard Langmuir-probe diagnostic procedures with pulse-mode operation. Circuit versatility provides the means for studying time-dependent phenomena and establishes an improved capability for measuring plasma density and temperature. As an application of the circuit, it is shown that pulse-mode operation reduces the time variance of electrode surface conditions which often cause hysteresis in the Langmuir-probe current-voltage characteristic.

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CONTENTS

CIRCUIT DETAILS AND APPLICATION NOTE FOR A VERSATILE PLASMA PROBE

INTRODUCTION

The Langmuir probe [1] is an attractive experimental device with intrinsic diagnostic capabilities that are readily applied to laboratory [2,3] and ionospheric [4] plasma investigations. In its simplest form, the probe is a metallic electrode, of cylindrical, planar, or spherical geometry, which collects current from a plasma when a voltage is applied.

The nature of a particular probe experiment determines the exact manner in which the probe voltage is applied. A continuous voltage sweep (with a period long compared to the electron plasma period) is often employed in a standard diagnostic approach [2] for measuring plasma density and temperature. On the other hand, higher sweep frequencies and pulse-mode operation are used to study the plasma response to time-dependent fields [5]. Pulse-mode operation can also be used to study macroscopic sorption phenomena and the resulting electrical perturbations associated with an active electrode in a plasma environment [6,7].

In this report we present a new Langmuir-probe circuit which can be used in all of the aforementioned areas of investigation. Its programmed modes of operation (Fig. 1) alternate between a continuous sawtooth sweep voltage and a pulse-modulation mode in which the pulse amplitude follows a sawtooth envelope. The continuous sweep represents the standard approach to Langmuir-probe diagnostics, whereas the pulse procedure is an improved diagnostic tool with capabilities for studying time-varying phenomena, whether they be the plasma's ability to respond to pulsed and RF electric fields or the time variation of electrode surface conditions resulting from neutral- and charged-particle bombardment.

The electronic format in the pulse-modulated mode presents consecutive sequences of four pulses which generate distinct I-V data points for the probe's current-voltage characteristic. The fifth pulse is blanked out so that current I_B, collected at a fixed baseline voltage V_B during the interpulse periods, can be monitored and used as a measure of possible variations in the probe-plasma system. The duration of a sweep pulse τ_{on} (Fig. 2), as well as its repetition rate, can be varied over wide limits. The sweep time τ_S (Fig. 1), sweep amplitude $V_+ - V_-$, interpulse time τ_B (Fig. 2), and baseline voltage V_B can also be tailored to fit a given experiment or can be adjusted independently during an investigation. The probe current is always sampled during a subinterval within a sweep pulse, with the subinterval position τ_D and duration τ_i (Fig. 2) being separately adjustable. This current sampling also occurs in identical fashion during the period corresponding to the blanked-out fifth pulse.

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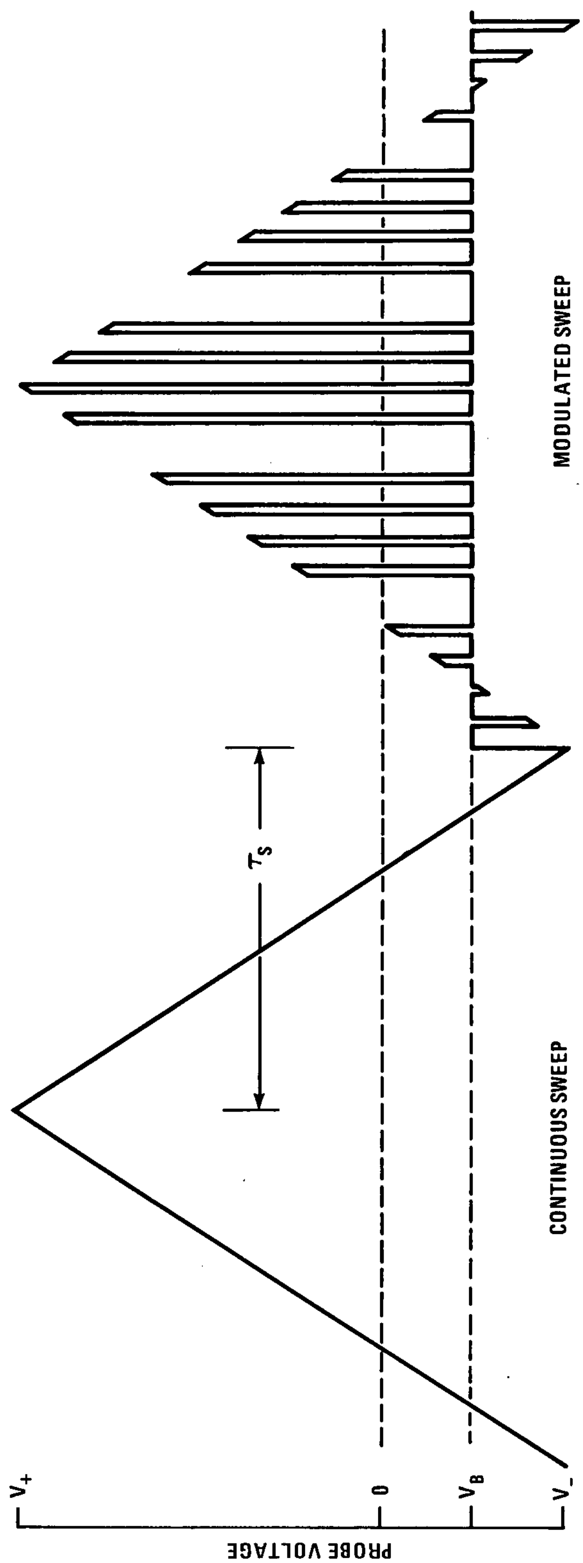


Fig. 1 — Continuous- and modulated-sweep modes of probe operation

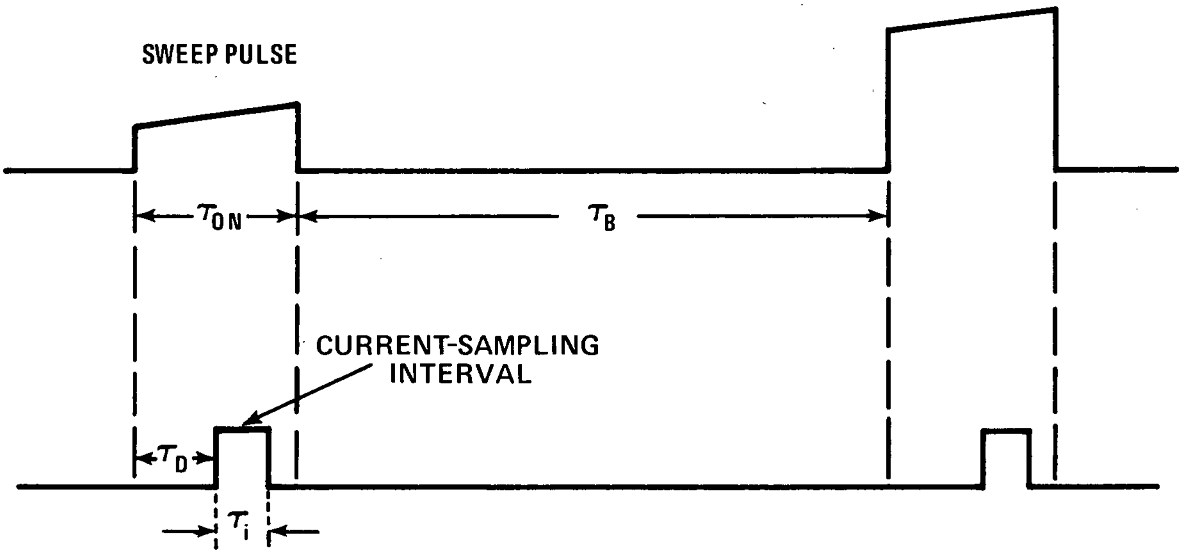


Fig. 2 — Expanded time scale of the sweep pulses of Fig. 1 shown relative to the current-sampling interval

The versatility of our circuit allows the following specific applications:

- Variability in τ_s of the continuous-sawtooth mode permits studies of the response of plasma sheaths at both low and high frequencies;

- Variability of the ratio τ_{on}/τ_B permits an evaluation of charging effects on contaminated surfaces, and the alternate-mode capability (continuous sawtooth followed by pulse modulation) permits direct and immediate comparison of the two approaches for collecting Langmuir-probe characteristics;

- The variability in τ_i and τ_D makes possible the study of plasma response to pulsed electric fields*

- Measurement of the baseline current I_B permits a standard retarding-field analysis of electron energy, even under conditions of fluctuating plasma densities. (Because the running measurement of I_B throughout the pulse-modulated sweep provides a direct relative measure of the ambient plasma density, fluctuating plasma densities can be unfolded from the resulting current-voltage characteristic, provided the fluctuations are approximately linear between adjacent values of I_B. In our studies, this constraint was satisfied by measuring I_B at approximately 10-ms intervals.)

*It should be noted that the sawtooth envelope precludes a perfectly square pulse. However, in our applications the pulse height and width and the time rate of voltage variation in the sawtooth envelope were such that the pulse could be considered square.

In the sections that follow, a general and detailed circuit description is presented, and a specific application of our pulse-modulated approach to probe diagnostics in contaminating plasma environments is described.

GENERAL CIRCUIT OPERATION

Figure 3 is a simplified block diagram of the instrument. The probe-voltage sweep, described in the Introduction, is produced by a linear-sweep generator which is interrupted sequentially by the modulator when operation is in the pulsed-sweep mode. The modulator pulse (100 μs) is generated by a repetitively triggered multivibrator. A separate multivibrator, synchronized with the sweep pulse, establishes the sampling interval (50 μs) during which the probe current is measured and stored (Fig. 2). Logic circuits program the instrument to alternate between the pulse-modulated-sweep mode and the continuous-sweep mode, with probe-current sampling in either mode occurring during the current-sampling interval only. The modulator pulse and probe-current-sampling repetition rates are equal to that of an externally generated master pulse.

Through electronic switches S_1 and S_2 the Langmuir probe is connected to one of two electrometers with sensitivities which differ by a factor of 100. A differential amplifier converts the floating electrometer output voltage to a ground-referenced-voltage signal, the polarity of which is monitored. The signal itself is full-wave rectified so that both positive- and negative-current signals appear with positive polarity. This obviates the need for mirror-image circuits in processing bipolar signals.

The rectified signal is then sent to three parallel amplifiers having gains of 25, 5, and 1 respectively. The gain selector sends to the storage circuit the output signal from the highest gain amplifier that is not in signal saturation. The storage circuit holds the signal value until the next probe-current sampletime arrives.

Through appropriate logic circuits, a signal that exceeds the range of the $\times 1$ amplifier switches the probe from the high-sensitivity to the low-sensitivity electrometer. If the $\times 25$ amplifier signal falls below a certain fixed value, the higher sensitivity electrometer is restored to operation. With the electrometer and amplifier gain ratios set at 100/1 and 25/1 respectively, Langmuir-probe input currents with an amplitude range of 2500 arrive at the instrument output with comparable amplitudes. The individual experimenter can select a different dynamic range by simply changing the values of resistors in the electrometers and amplifiers.

An advantage of the electrometer-selection logic is that electrometer switching never occurs while probe current is actually being measured. If for instance, a probe-current sample saturates the $\times 1$ (least sensitive) amplifier, then the less sensitive electrometer is switched into the circuit immediately following the sweep pulse so that switching transients will have settled down by the time the next sweep pulse arrives. Because the value of the probe current measured during a sweep pulse is most often quite different from that measured during a blanked-out (baseline voltage) pulse, the logic is programmed to separate the required electrometer switching information for pulses 1, 2, 3, and 4 from

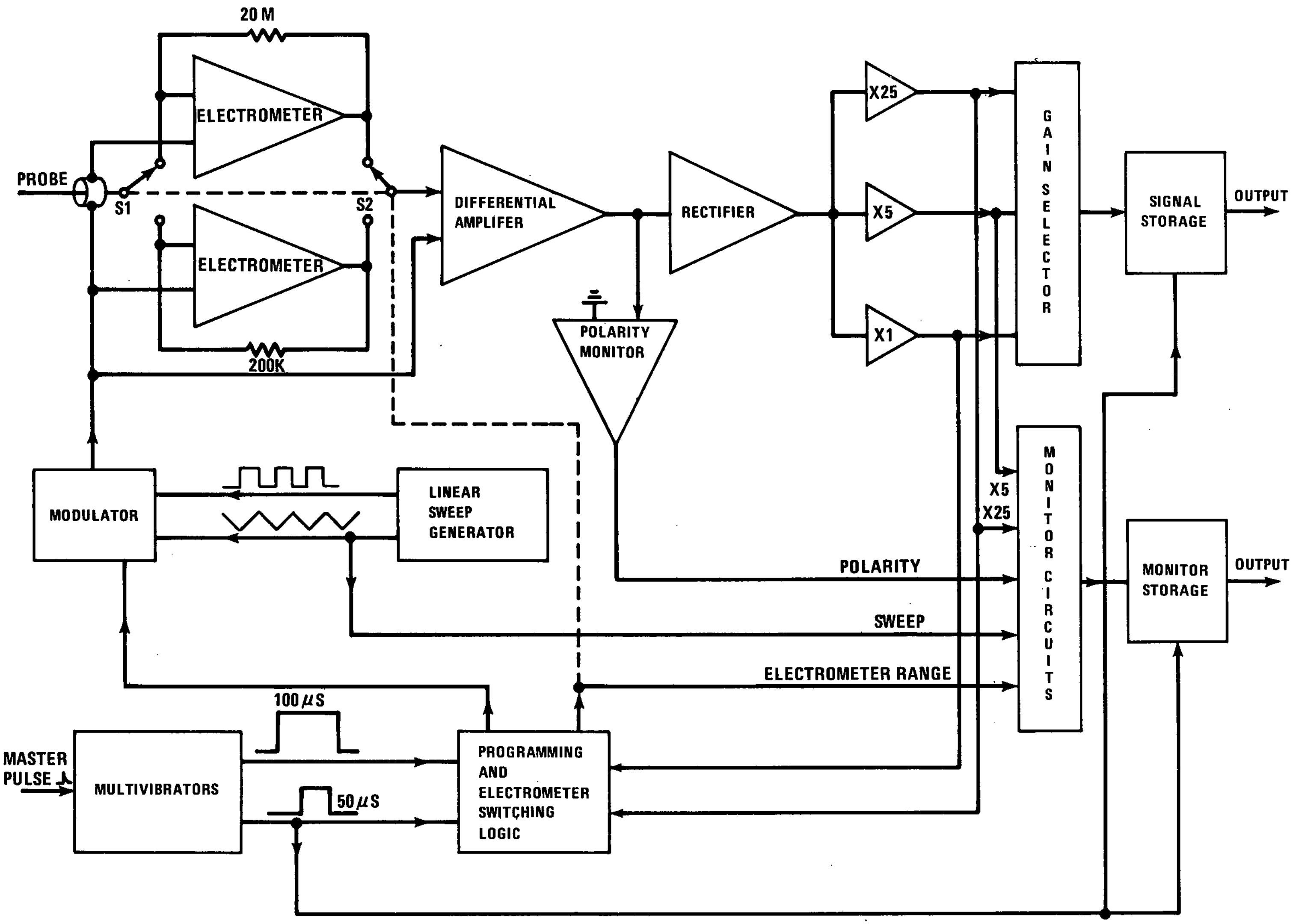


Fig. 3 — Simplified block diagram of the probe electronics

that for the "missing" pulse 5. Thus prior to the occurrence of a probe-current measurement at the baseline voltage V_B (pulse 5), circuit logic has already selected the electrometer specified by the value of the probe current measured during the previous pulse 5. Likewise, prior to the occurrence of pulses 1, 2, 3, or 4, electrometer switching will have been governed by the probe current measured during pulses 4, 1, 2, or 3 respectively.

For each measurement of probe current, the selected values of amplifier gain, electrometer sensitivity, signal polarity, and sweep voltage must be known. These functions are monitored and stored in a second storage unit used for that purpose.

CIRCUIT DETAILS

Sweep Circuits

The circuit of Fig. 4 produces a linear sweep voltage at a sweep rate inversely proportional to the product $R_5C_5 \approx \tau_s$ (Fig. 1), with voltage limits V_- and V_+ (Fig. 1) determined by voltage V_z and resistors R_1, R_2, R_3, and R_4. Operational amplifier 1, a linear integrator, determines the sweep rate; amplifier 2 reverses the sweep direction at voltage limits V_- and V_+. The output excursion of amplifier 2 is limited by two diodes to slightly more than V_z. With V_z fixed, the ratio R_1/R_2 determines the peak-to-peak sweep-voltage excursion, and the ratio R_3/R_4 sets the voltage about which the excursion is centered. If $R_6 = R_7$, the slopes of the positive- and negative-going sweeps are equal in absolute value. The square-wave output from amplifier 2 is rendered TTL compatible by the 4.5-V zener-diode/diode network.

An externally generated master pulse (Fig. 5) determines the probe current-sampling rate for the instrument and triggers the pulse sequence of Fig. 2. A multivibrator produces the sweep modulation pulse, the length of which is determined by R_1C_1 and is set to 100 μs in this instrument. A second multivibrator determines the time delay between initiation of the sweep pulse and the beginning of the probe current-sampling interval; this delay is determined by R_2C_2 and is set to 40 μs. A third multivibrator generates the probe current-sampling interval, which is controlled by R_3C_3, and is set in this case to 50 μs. This current-sampling pulse, which enables the signal and monitor sample-and-hold circuits, terminates 10 μs before the end of the 100 μs sweep pulse and thus avoids the signal and monitor transients that accompany the termination of the sweep pulse itself.

The count-of-five circuit in Fig. 5 comprises three flip-flops. As shown in the accompanying truth table, output $\overline{Q}_3$ provides the logic input to the sweep modulator (Fig. 6), which blanks out pulse 5 (every 5th pulse). (Flip-flop 4 is part of the sweep modulator.)

Figure 6 details the sweep modulator and shows the transistor switch, which in an opened state maintains a fixed voltage V_B on the sweep bus. This fixed-voltage level is established by the $R_1:R_2$ divider network. Modulation of the sweep is accomplished by closing the switch and connecting the sawtooth voltage (Fig. 4) to the sweep bus (Fig. 6) only during a 100-μs sweep pulse. In this particular instrument a pulse-modulated

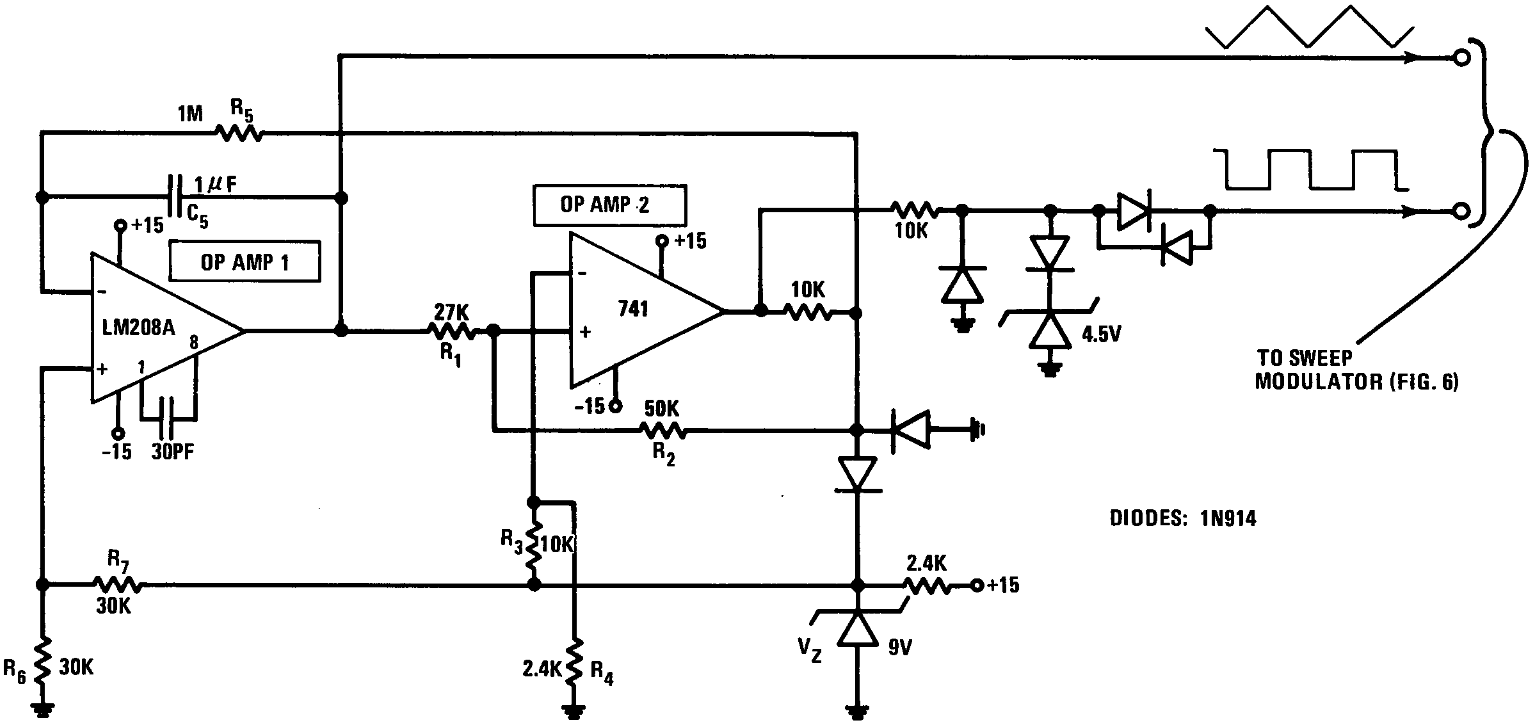
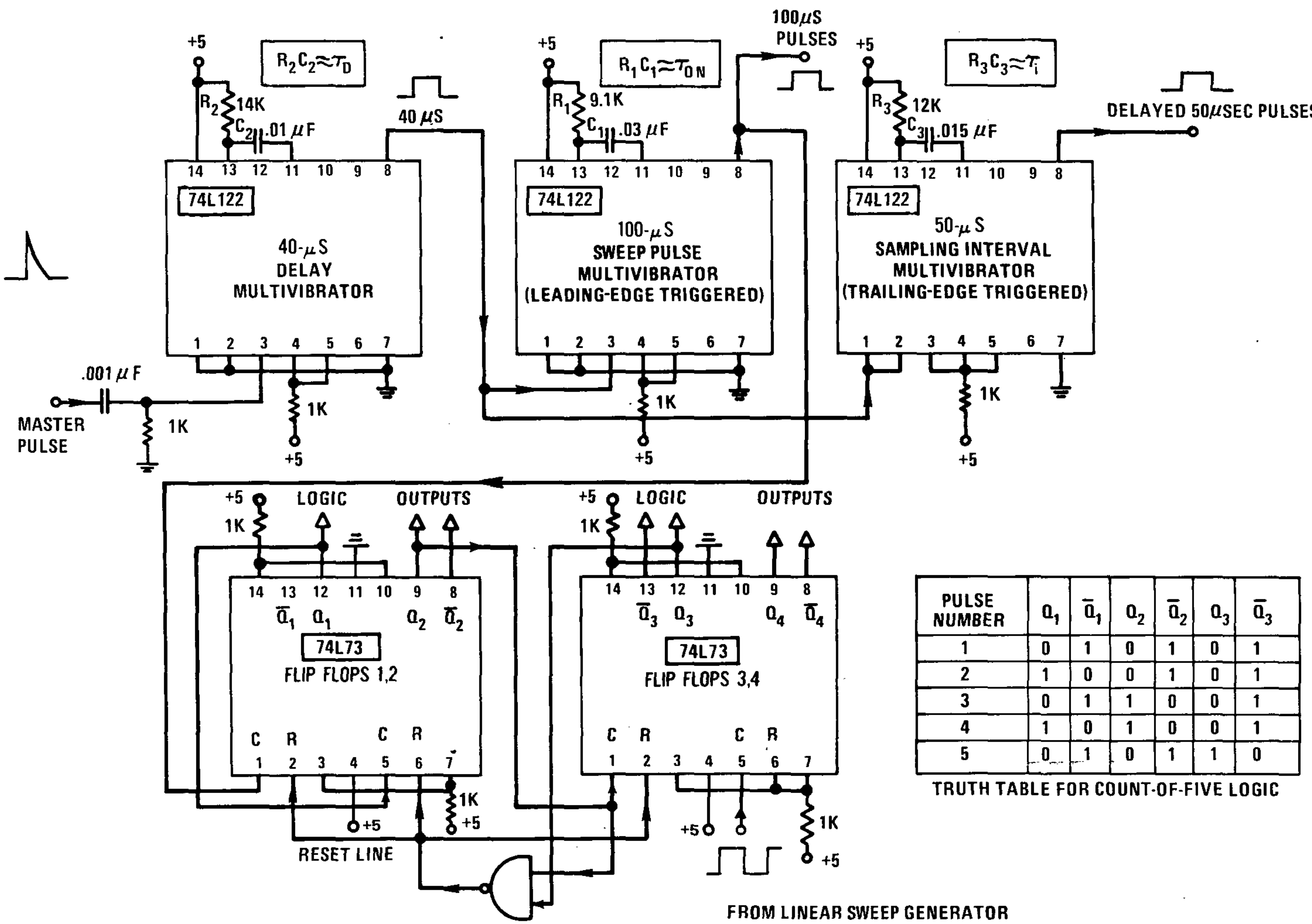


Fig. 4 — Generator for the linear, symmetric, sawtooth sweep



PULSE NUMBER	Q_1	$\bar{Q}_1$	Q_2	$\bar{Q}_2$	Q_3	$\bar{Q}_3$
1	0	1	0	1	0	1
2	1	0	0	1	0	1
3	0	1	1	0	0	1
4	1	0	1	0	0	1
5	0	1	0	1	1	0

TRUTH TABLE FOR COUNT-OF-FIVE LOGIC

FROM LINEAR SWEEP GENERATOR
(SEE FIGS. 4 AND 6)

Fig. 5 — Multivibrators, count-of-five logic, and flip-flop 4.
Arrows represent signal paths.

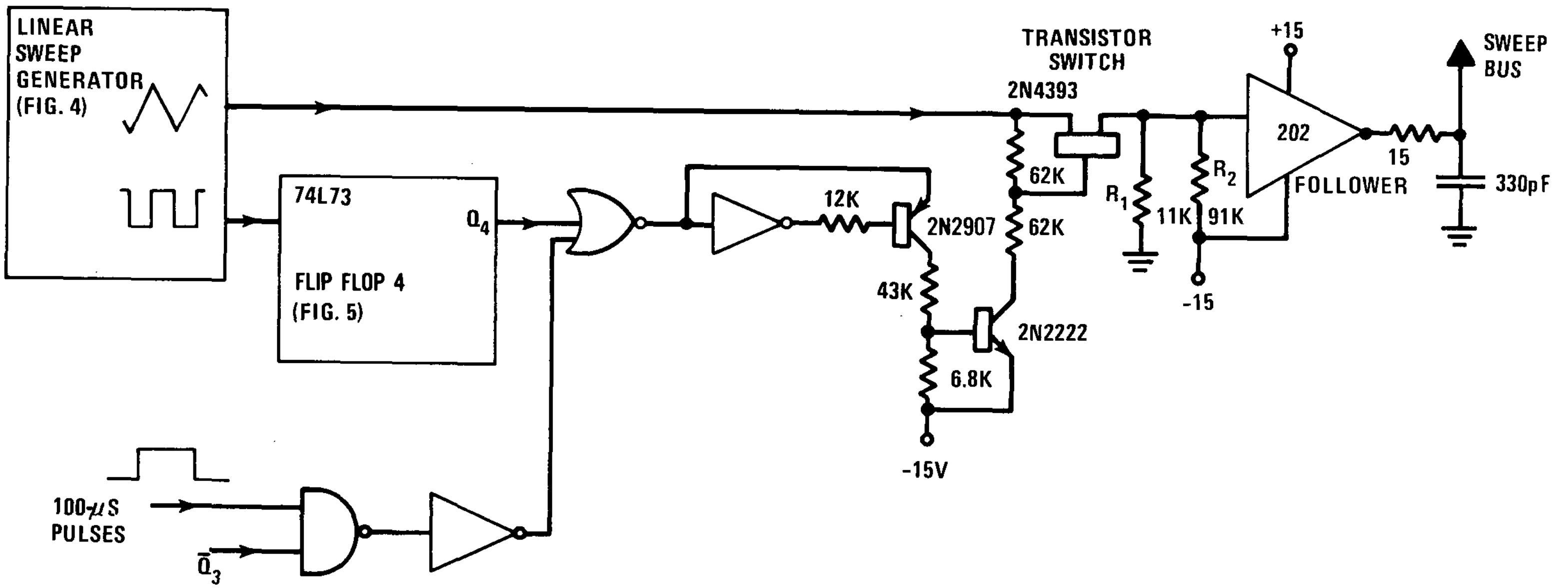


Fig. 6 — Sweep modulator

sweep alternates with a conventional linear (unmodulated) sweep. Flip-flop 4 (Fig. 5) disables the modulator on alternate cycles of the linear-sweep generator (Fig. 4 through 6). During modulation, the 100-μs sweep pulses close the transistor switch (Fig. 6), leaving it open during the interpulse interval. Pulse 5 is blanked out by the logic input from $\overline{Q}_3$. During alternate sweeps, the transistor switch is closed, and the continuous linear sweep (Fig. 4) is sent unaltered to the sweep bus (Fig. 6). During the continuous sweep, the pulse sequence (Fig. 2) continues uninterrupted, and the probe current is sampled during the sampling interval only, just as it is in the pulsed-sweep mode.

Electrometers

The high- and low-sensitivity electrometers (Fig. 7) are connected and disconnected by means of transistor switches in both the input and output leads; positive voltage on line B connects the high-sensitivity electrometer into the circuit.

An Analog Devices type 516 FET high-speed operational amplifier is used for the high-sensitivity electrometer. Zener-diode limiters shunt the 20-MΩ feedback impedance during large instantaneous capacitive input currents caused by the leading edge of the sweep pulse. Without limiters, recovery from such transients may be too slow; recovery in the less sensitive electrometer is sufficiently fast.

The electrometer output signal and the sweep voltage are sent to the differential amplifier for sweep-voltage subtraction. The resulting signal voltage is referenced to ground and proceeds to the comparator for detection of changes in signal polarity and to an analog full-wave rectifier which transmits incoming positive signals and inverts those of negative polarity. The full-wave rectified signal is sent to the scale changer.

Scale Changer

Three separate amplifiers (Fig. 8), having gains of 25, 5, and 1 respectively, have a common input terminal and provide a convenient dynamic range to bridge and extend the 100-to-1 sensitivity difference between the two electrometers. Transistor switches in each amplifier output connect the most sensitive amplifier having an on-range signal to a common output line which is the input to the sample-and-hold data-output circuit. During each 50-μs current-sampling pulse, the voltage on the sample-and-hold input is stored and held. The particular amplifier in use at this time is identified by monitor voltages sent to the monitor sample-and-hold circuit.

Electrometer Switch Logic

On the basis of the signal level measured during the sampling pulse, this circuit decides which electrometer shall be used for the next sample pulse. If the signal from the $\times 1$ amplifier is greater than 4.9 V (of a maximum range of 5.0 V), then the low-sensitivity electrometer will be used for the next try. If, on the other hand, the signal from the $\times 25$ amplifier is less than 1.0 V, then the more sensitive electrometer will be tried next.

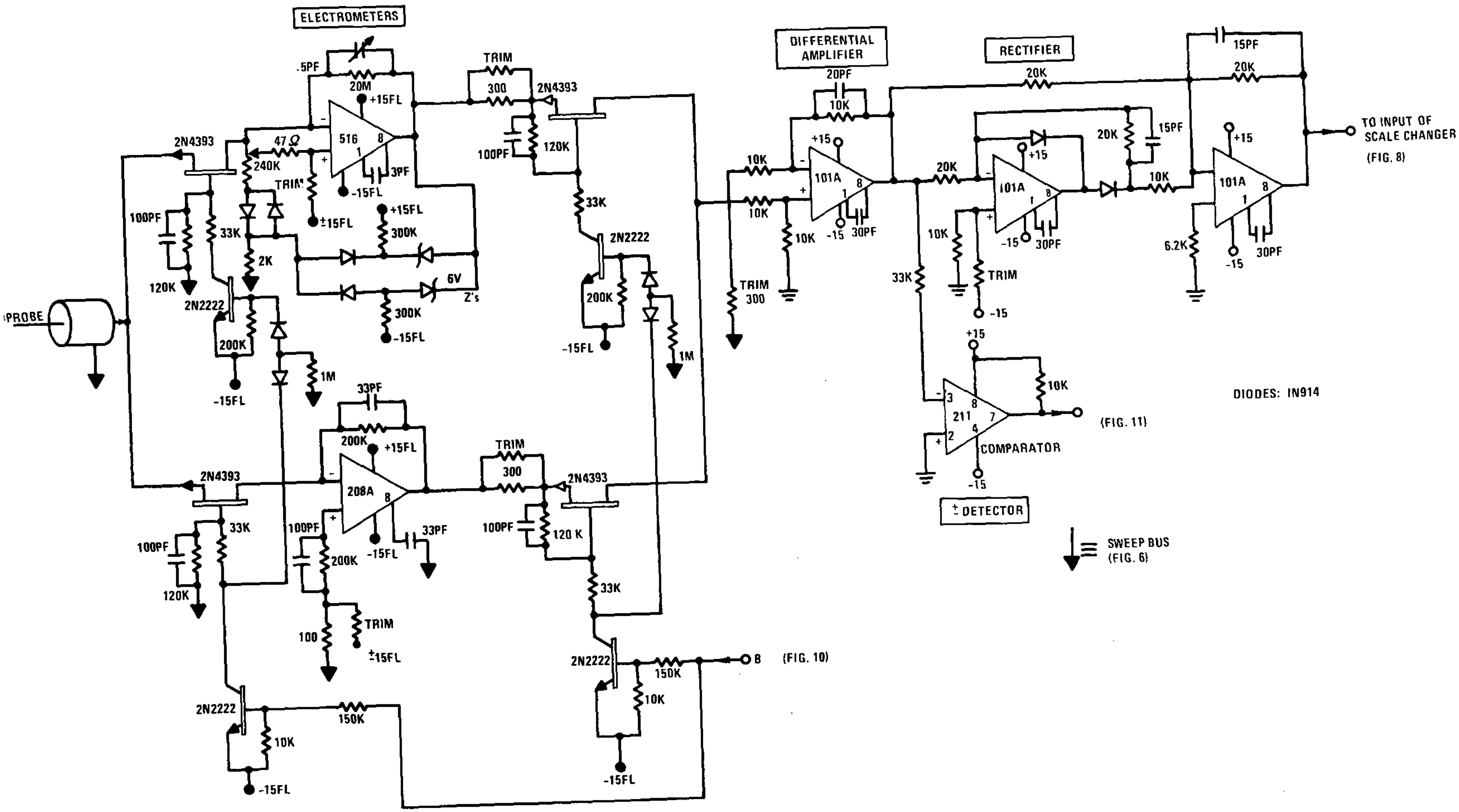


Fig. 7 — Electrometers, differential amplifier, rectifier, and polarity detector

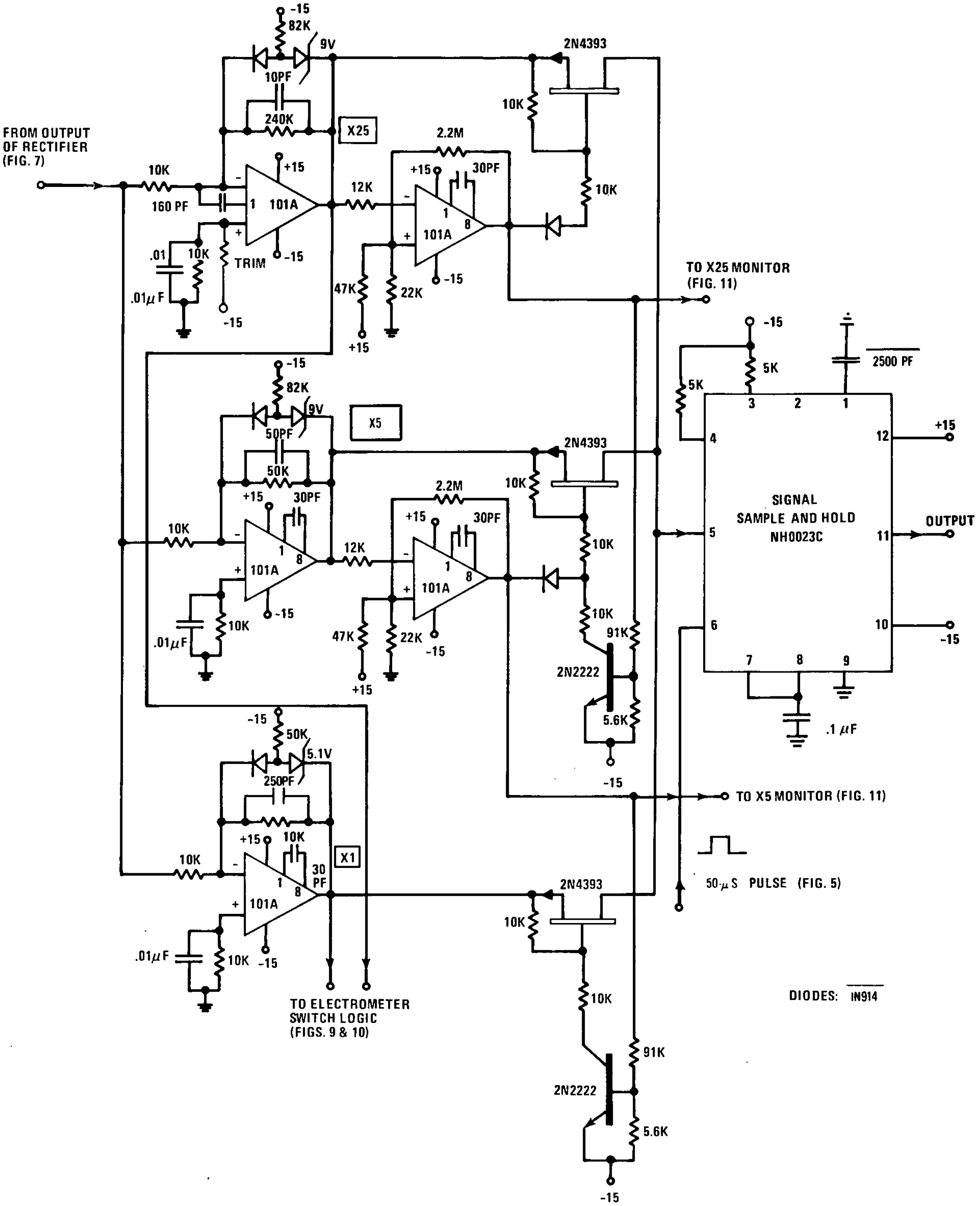


Fig. 8 — Scale changer

Electrometer switching takes place on the trailing edge of the sweep pulse, a few microseconds after the signal sample has been taken. This allows time for the new electrometer to settle down before the next sampling pulse arrives. As was discussed in the Introduction, storage of electrometer-switching information for the blanked-out pulse 5 is separate from storage for pulses 1, 2, 3, and 4. Figure 9 outlines this logic, and Fig. 10 details the electronics.

The signal-level switching information from the $\times 25$ and $\times 1$ amplifiers is held in bilevel Schmitt storage circuits (Figs. 9 and 10) which, at the termination of the sweep pulse, flip the electrometer switch (also a Schmitt circuit) to the state identical to that of the storage circuit. Storage for pulses 1, 2, 3, and 4 is one Schmitt circuit, and storage for pulse 5 is the other.

It should be noted that the storage-circuit input gates conduct during the sampling pulse, whereas the storage-circuit output gates conduct during the differentiated trailing edge of the sweep pulse. Logic for these gates originates at the count-of-five outputs which are labeled in Fig. 10.

Monitors

From a reading of the monitor output voltage (Fig. 11), one can determine:

1. Whether the probe current is positive or negative.
2. Which electrometer is connected into the circuit.
3. Whether the $\times 25$ amplifier is off range.
4. Whether the $\times 5$ amplifier is off range.

Each of these four monitored binary functions turns "on" or "off" its own constant-current generator which feeds common resistor R. The voltage across R is sampled and stored during each sampling pulse. For appropriately chosen values of constant current, each combination of possible states of these four functions produces its own unique voltage across R. During the occurrence of each pulse 2 (of the count of five), the switch connects the sweep voltage to the sample-and-hold monitor circuit so that of each five monitor samples, one of them is equal to the instantaneous value of the sweep voltage.

Power Supplies

This instrument requires 15-V positive and negative supplies for the operational amplifiers and a positive 5-V supply for the TTL logic. Because the two electrometer circuits are themselves referenced to the sweep voltage rather than to ground, it is necessary that the power supplies for the electrometers be separate from those that serve the rest of the instrument and that they have high capacitive reactance to ground. The common terminal of the positive and negative 15-V electrometer supplies is connected to the sweep voltage rather than to ground.

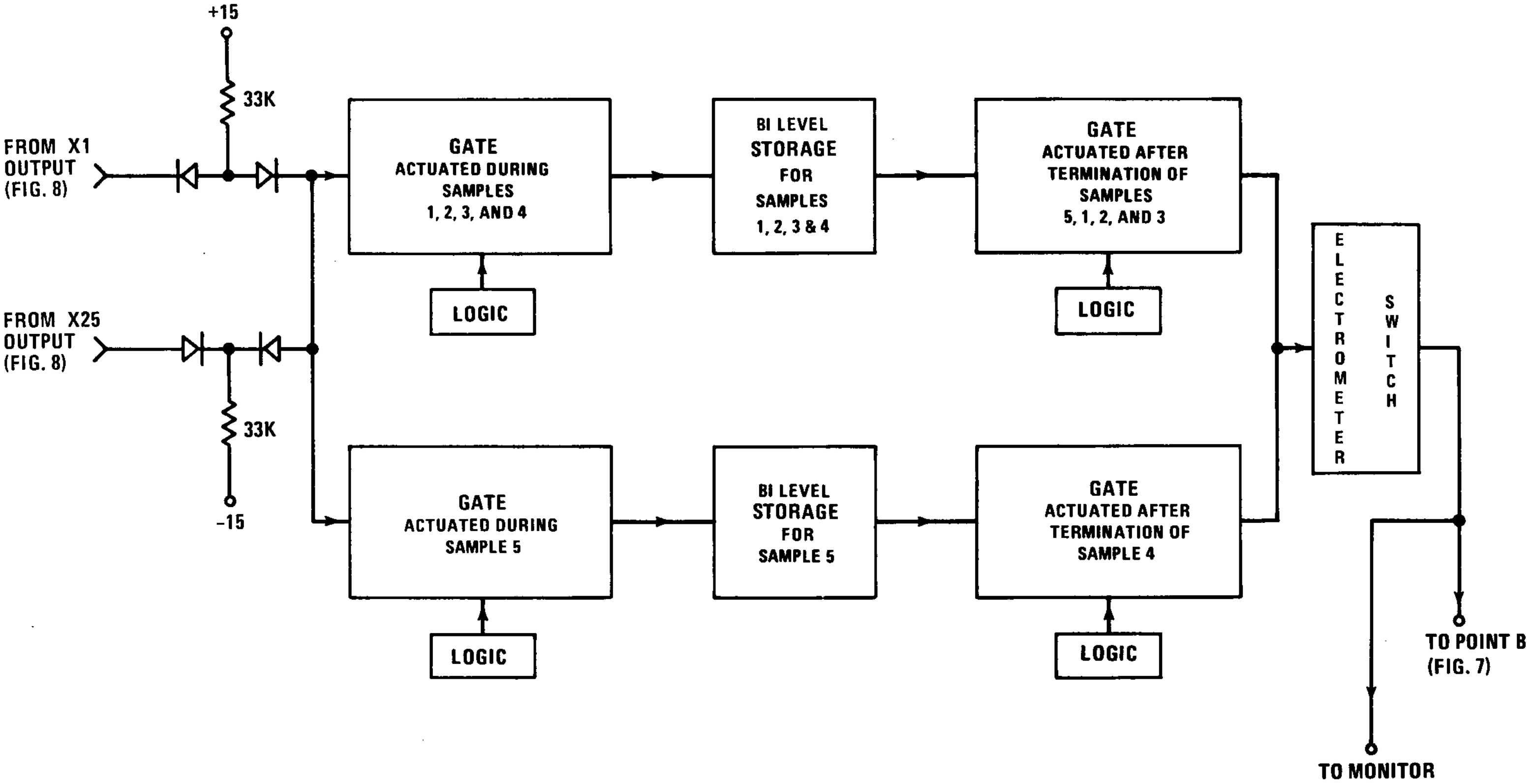


Fig. 9 — Electrometer switch logic

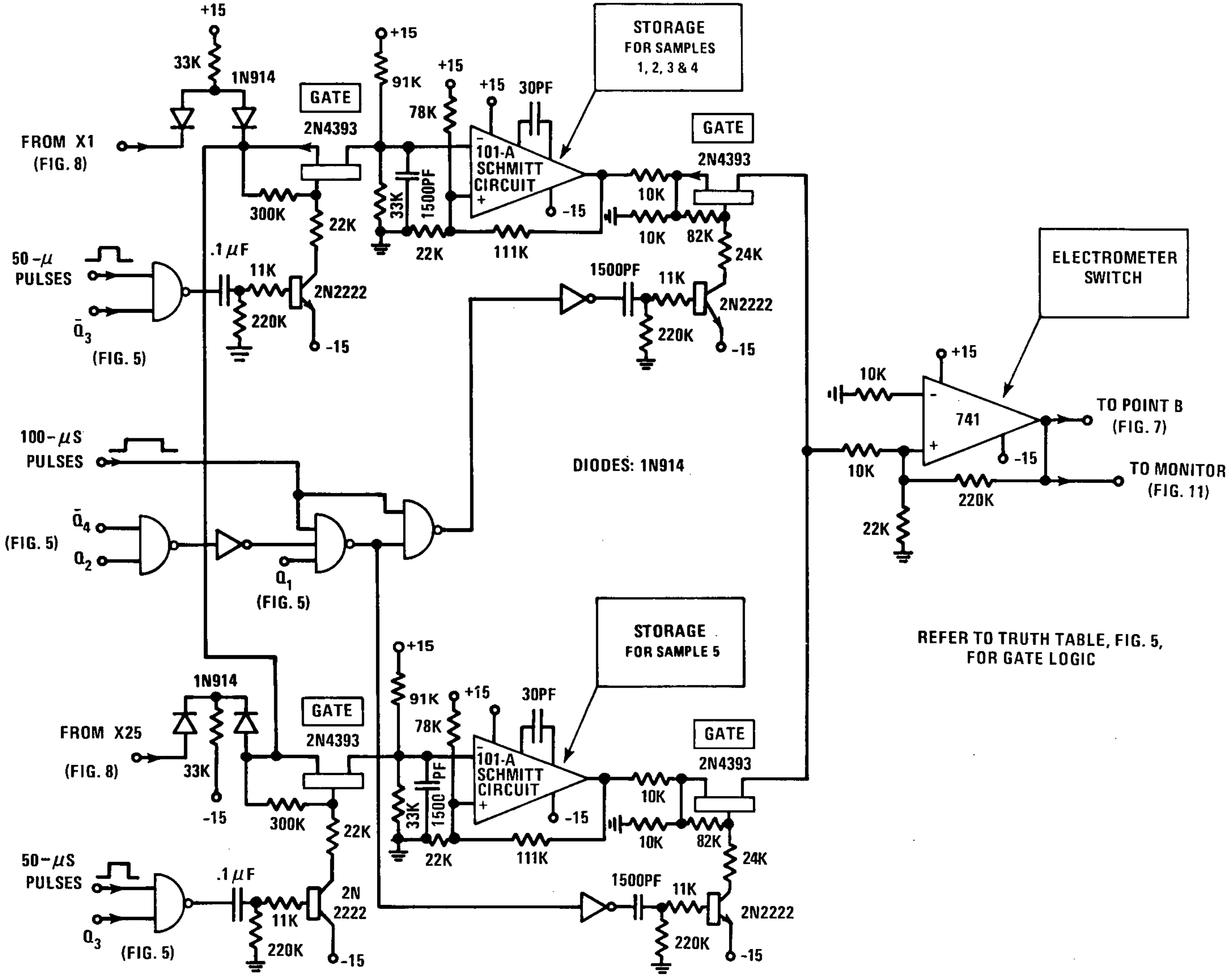


Fig. 10 — Electrometer switch logic

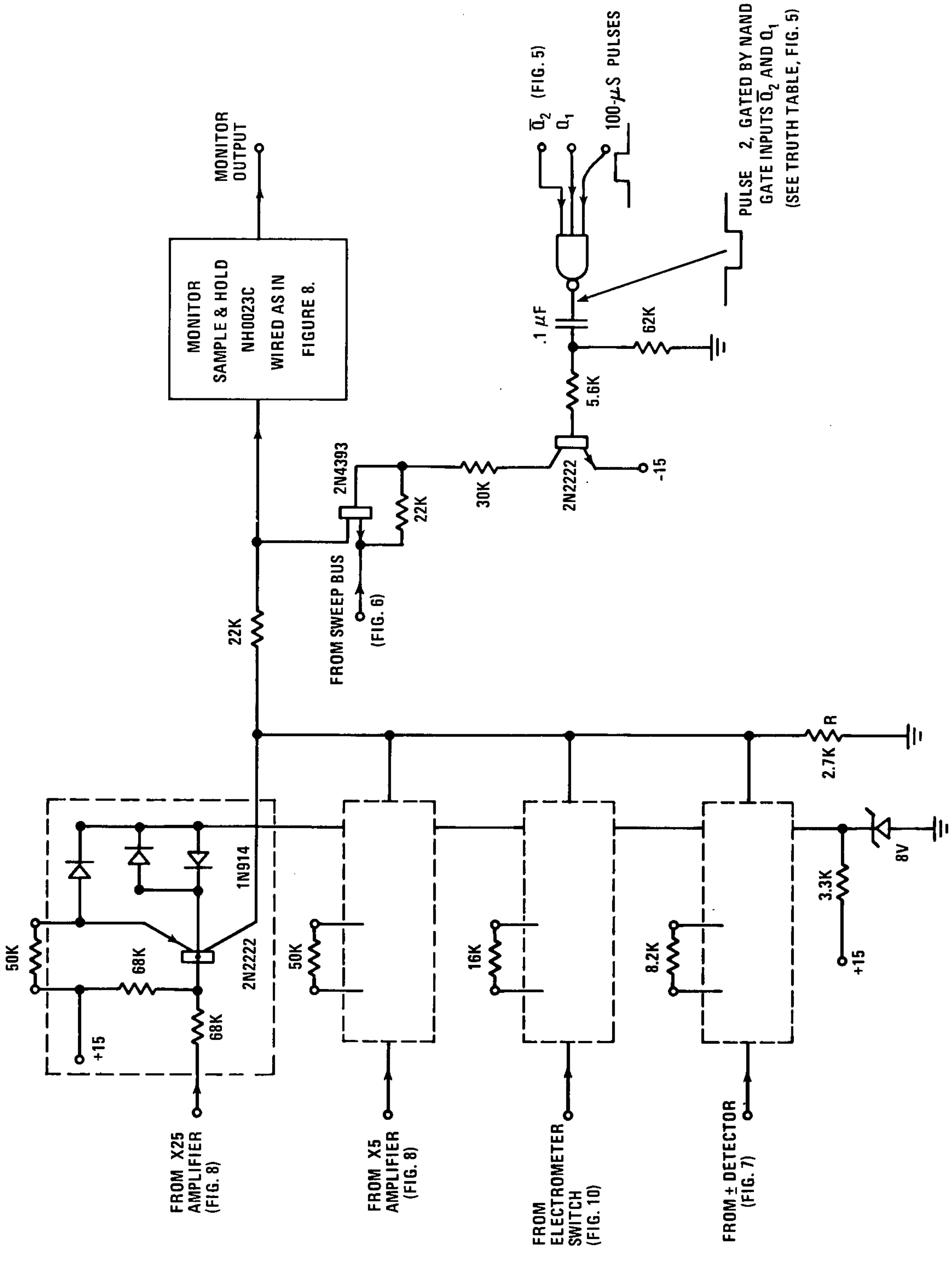


Fig. 11 — Monitors

AN APPLICATION

There is considerable evidence that the standard continuous-sweep approach to Langmuir-probe diagnostics [6 - 10] can lead to serious distortions of the current-voltage characteristic measured in contaminating plasma environments. These distortions manifest themselves as hysteresis in the current-voltage characteristic, with the phenomenon frequently interpreted in terms of a parallel-RC-circuit model for the contaminated probe surface. There are several approaches to circumventing this problem [6], one of them being the pulse-mode operation depicted in Fig. 2.

The instrument described in this report can demonstrate the effects of surface contamination of the probe. Figure 12 is an actual recorder trace of the probe current collection in a plasma generated by electron bombardment of air at 0.66-Pa (5×10^{-3} Torr) pressure. Range switching prevents off-scale signals and accounts for the discontinuities of the recorder traces. Both electron and ion currents are displayed as positive signals. With reference to Fig. 12, the voltage sweep sequence begins at point 1 in the modulated mode at the most negative voltage V_-. At this point, current collection is in the net-ion phase. Moving to the left, the voltage becomes more positive, and the ion current decreases until at point 2 the floating potential is reached. As the voltage becomes still more positive, net electron current flows to the probe, continuing to increase (going through a range switch at point 3) until its peak value is reached at point 4, which is coincident with the most positive sweep voltage V_+. The sweep reverses direction and retraces itself, going from maximum positive to maximum negative voltage. At point 7, sweep pulse modulation ceases. The continuous sawtooth sweep begins there at V_-, peaks in electron current at point 8 (V_+), and retraces itself to its maximum negative value V_- at point 9.

The striking features in Fig. 12 are the differences in peak amplitude and symmetry between the two modes of operation; the conventional sawtooth sweep produces very significant hysteresis, whereas the modulated sweep does not. As regards derived temperatures and densities, the conventional approach is clearly ambiguous. A close examination of the modulated-sweep trace reveals some nonsymmetry in those regions within 20 ms (τ_s = 275 ms) of sweep-mode switchover points 1 and 7 (compare the regions $[t_1 + 20 \text{ ms}] \geqslant t \geqslant t_1$ and $[t_7 - 20 \text{ ms}] \leqslant t < t_7$). The former period is the length of time required for the probe to "forget" its surface condition established during the preceding continuous sweep. Since this recording was made, we have programmed the sweep sequence so that each mode operates through two cycles, rather than one complete cycle. Only the very beginning of the first modulated-sweep cycle suffers memory effects from surface conditions acquired during the preceding conventional sawtooth sweep. The result is 100% symmetry of the second modulated sweep. We have established similar results in air, helium, argon, and carbon dioxide plasmas.

Our contention that the elimination of hysteresis by pulse modulation was a result of stabilized electrode surface conditions and not some other phenomenon was tested in a number of ways:

1. The current-sampling interval τ_i (Fig. 2) was positioned at various locations within the sweep pulse τ_{on} by selecting different values of τ_d for identical plasma

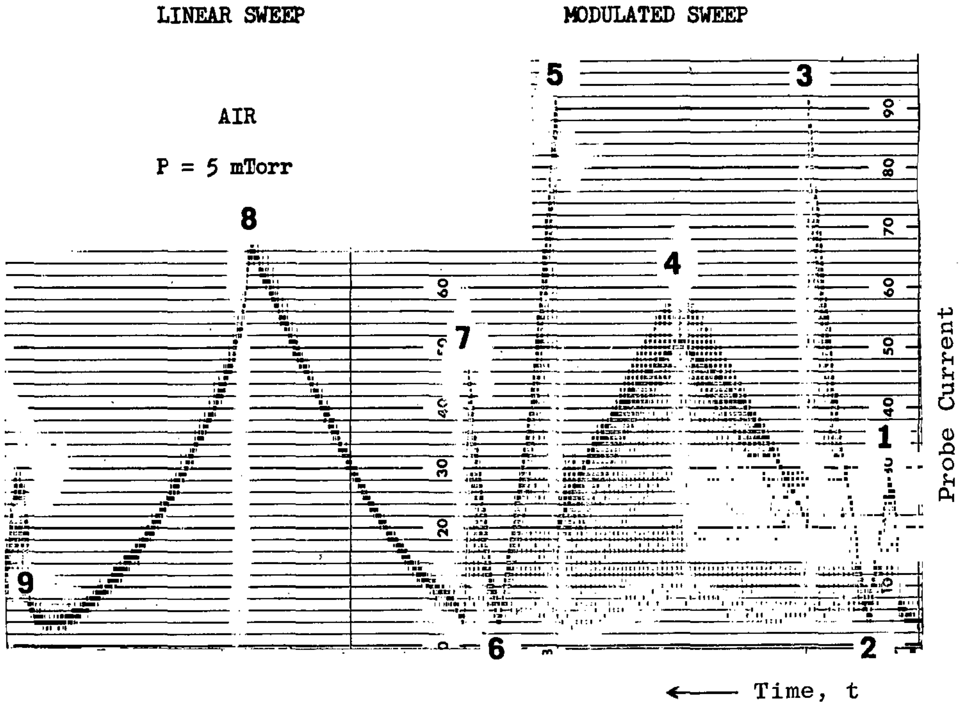


Fig. 12 — Recorder trace of the probe current in a plasma using pulsed and continuous sweeps

conditions. With τ_{on} and τ_i equal to 102 and 45 μs respectively, τ_d was set at 14, 24, 34 and 44 μs, and complete I-V characteristics were collected for each case. That all characteristics were found to be identical supported the assumption that we were not sampling some transient plasma state (which would be the case if τ_{on} or τ_d or both were less than the inverse ion plasma frequency v_{pi}^{-1}) nor perturbing our measurement with sizeable displacement currents through stray circuit capacitances. The possibility of the latter distortion was also eliminated by simply shunting the probe terminal through a resistor R to ground. Under this condition the modulated and continuous modes yielded linear and identical I-V characteristics with $dI/dV = R^{-1}$.

2. A more convincing test resulted from plasma sampling by the continuous and pulse-modulated modes under both cleaned- and uncleaned-probe-surface conditions. Immediately after a probe-cleaning procedure of resistive heating, the I-V characteristics of both modes were found to be identical, but continued exposure (on a time scale of seconds) of the probe to the charged- and neutral-particle environment of the plasma chamber showed increased degradation in the symmetry of the continuous mode, finally resulting in hysteresis like that shown in Fig. 12. There was no corresponding symmetry loss in the pulse-modulated mode. The details of these and related tests will be presented in another article which deals with the mechanisms of surface contamination and associated charging effects.

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